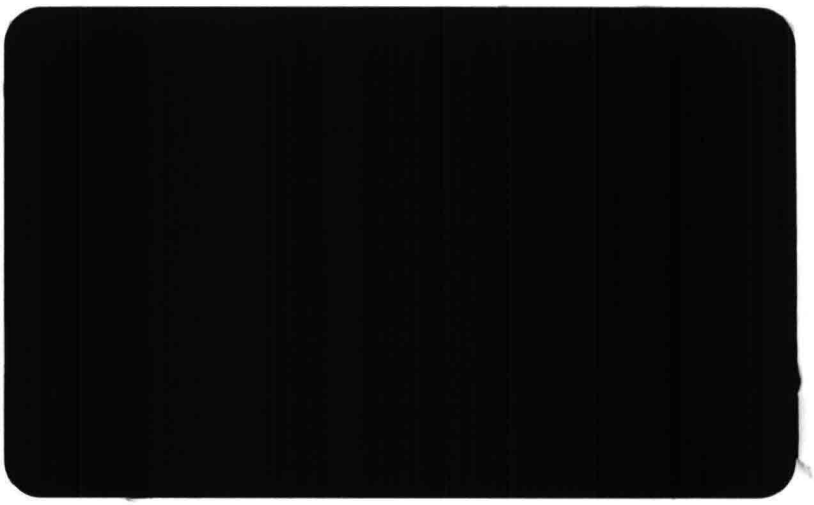

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Instruments used in the research on Cohesive Sediments

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Abstract

A research program was started to study the behaviour of cohesive sediments at the Delft University of Technology in 1989. As part of this project a well-provided physico-chemical laboratory was built within the Hydromechanics Laboratory and adequate instrumentation was purchased. These new instruments and other instruments already present in the laboratory were tested in order to check their operation in saline suspensions of China Clay, an artificial cohesive sediment.
Under these conditions the following instruments were tested and found in order for employment: an optical concentration meter (Oslim), an electromagnetic flowmeter, a thermometer, an electromagnetic velocity meter, a wave height meter and a pore-pressure meter.
Furthermore, some devices were tested for the determination of basic physico-chemical quantities, such as the pH, the suspended sediment concentration determined by filtration, the mass and the conductivity, for instance.
A description of these tests and some general specifications of the devices are presented in this report.

1. Introduction

For various reasons there has been a growing interest in the behaviour of cohesive sediments since a number of years. The costs for dredging cohesive sediments in navigational channels, for instance, are increasing every year and due to the high adsorptive capacity of the fine cohesive sediments for dissolved chemicals the dredged material may be highly contaminated. The disposal and cleaning of polluted mud has become a matter of deep concern and high costs.
In 1989 the Delft University of Technology granted funds for starting a research program on the behaviour of mud as part of a policy of stimulating selected research areas. With these funds several facilities were arranged within the Hydromechanics Laboratory of the Department of Civil Engineering. As part of this project a well-provided physico-chemical laboratory was built and adequate instrumentation was purchased.
In this report an overview will be given of the instruments used in the research on cohesive sediments present at the Hydromechanics Laboratory at the time of writing (August 1992). Furthermore some experiences gained with these instruments will be described.

2. Oslim

An Oslim is a device with which the suspended sediment concentration can be measured continuously in the laboratory. The name Oslim is deduced from the Dutch description of the device, namely "Optische SLIbMeter". The Oslim was developed at Delft Hydraulics and its function is based on the adsorption and reflection of light by the particles in suspension the concentration of which is to be measured.

2.1 Description

An Oslim comprises of a sensor and a signal processor. The sensor housing is made of brass and contains an infrared LED (Light Emitting Diode) and a photodiode facing each other. A glass tube is placed between the LED and the photodiode through which the suspension to be measured is pumped. An outline of the sensor is shown in figure 1.1.1.
The attenuation of the infrared light beam, caused by light adsorption and reflection from the particles, is an exponential function of the sediment concentration. The exact form of this function depends among other things on the particle size distribution and the composition of the sediment.
Two sensor types are available at Delft Hydraulics for measuring different ranges of suspended sediment concentrations, both being compatible with the signal processor. The most accurate sensor has a 5.0 mm inside glass-tube diameter and, according to the specifications, the maximum suspended sediment concentration is about 10 $kg \cdot m^{-3}$. The other sensor has a 1.6 mm inside glass-tube diameter and the maximal concentration is about 50 $kg \cdot m^{-3}$. The exact range of the two sensors is mainly determined by the composition of the suspension.
The sensor is connected with two screened cables to the signal processor. Via one cable the LED is supplied with a constant current and the other cable leads the signal of the photodiode to the signal processor. The signal is amplified and partly compensated for the exponential relation between the

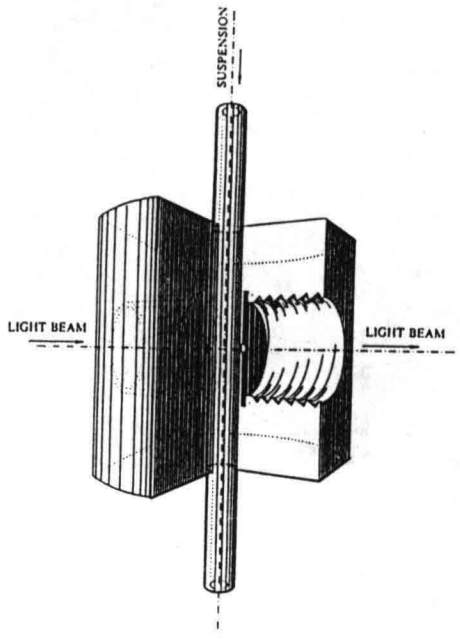

Figure 1.1.1 The Oslim sensor.

amount of adsorbed light and the sediment concentration. The analog output of the signal processor is available via a BNC socket and is in the range of 0 - 10 Vdc.
As all optical instruments, the Oslim is subjected to pollution of its glass tube. Therefore the suspension has to be pumped through the sensor at relatively high speeds. The supplier recommends a flow rate of at least 3 $cm^3 \cdot s^{-1}$ through the 5 mm glass tube and at least 1 $cm^3 \cdot s^{-1}$ for the 1.6 mm tube. Furthermore it is recommended to place the sensor in a vertical position. The device must be cleaned and calibrated at regular intervals.
According to the supplier [3] the range of operation varies between a few milligrams per litre up to at least 50 grams per litre, depending on the sensor configuration and composition of the sediment. The accuracy at the lowest and highest concentrations is $\pm$ 1 $mg \cdot l^{-1}$ and 50 $mg \cdot l^{-1}$, respectively.

2.2 Instructions for use

Before using an Oslim in an experiment it has to be adjusted and/or calibrated. For adjusting the Oslim, the maximal concentration of suspended material to be measured has to be known and the instructions, that will be described next, should be followed carefully [8].

- Connect the adaptor cable to the signal processor, before the adaptor is plugged into the mains-connector.
- Allow the device to warm up for about 30 minutes.
- Pump clean water through the sensor.
- Place the "ZERO" switch in position 1 when using an 1.6 mm sensor, otherwise place the switch in position 3.
- Place the "SPAN" switch at "x100" and the dial at 500.
- Adjust the output reading to 0.0 Vdc with potentiometer "ZERO". If the reading can not be adjusted to zero, but stays positive, the sensor has to be cleaned.
- Place the "SPAN" switch at "x10".

- Pump the suspension with the maximal concentration to be measured through the sensor. Adjust the output reading to 10.0 Vdc with the "SPAN" dial. If this is not possible the "SPAN" switch can be placed at "x100".

After this procedure the Oslim is ready for employment.
For accurate measurements it is recommended to calibrate the Oslim. The calibration of the Oslim has to be carried out with exactly the same material as used in the experiment. If the material is only available after an experiment, the Oslim can be calibrated afterwards, but attention must be paid to not changing the settings. However, the best way of calibrating an Oslim is during the actual experiment. If the variation of the concentration in time is not very large, the Oslim can be installed in such a way that the concentration is measured continuously and a sample can be taken when ever required. In this way a number of samples is produced of which the reading of the Oslim is known. After the experiment the concentration of the samples is determined and with these results a calibration curve can be generated.

2.3 Experiences

As mentioned before the suspension to be measured has to be pumped through the glass tube with a certain flow rate. In the Hydromechanics Laboratory a peristaltic pump with an adjustable flow rate (VELP Scientifica SP311/60, [21]) is used in combination with an Oslim.

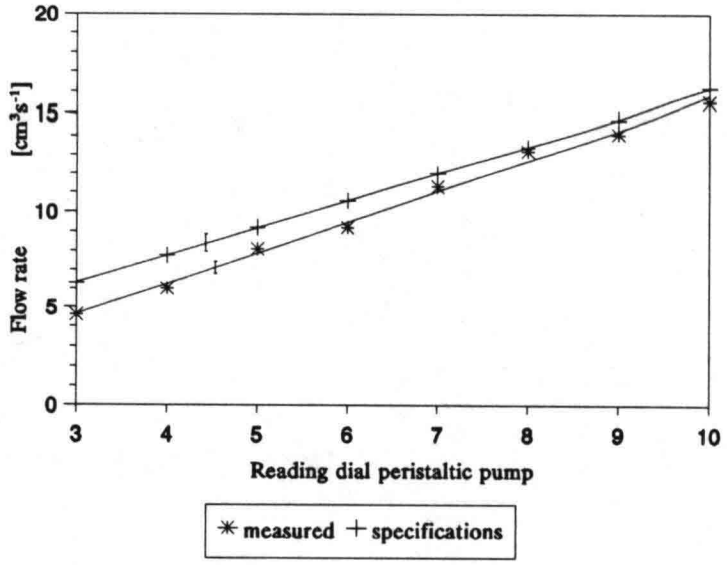

Figure 2.3.1 Performance Velp pump compared with the specifications.

Prior to using this pump with an Oslim, it was checked and calibrated. The flow rate of the pump in combination with the Oslim sensor at a certain reading of the dial (0 - 10) was determined using tap water and compared with the specification provided by the supplier. The results of this test, see figure 2.3.1, showed that the measurements almost correspond with the specifications.
In order to get any insight into the characteristics of an Oslim several tests were carried out; The influence of the flow velocity and flow direction in the sensor on the reading of the Oslim was studied and tests were carried out to study the accuracy of a 1.6 mm and 5.0 mm sensor for different

concentrations. A description of these tests will be given in the next sections.

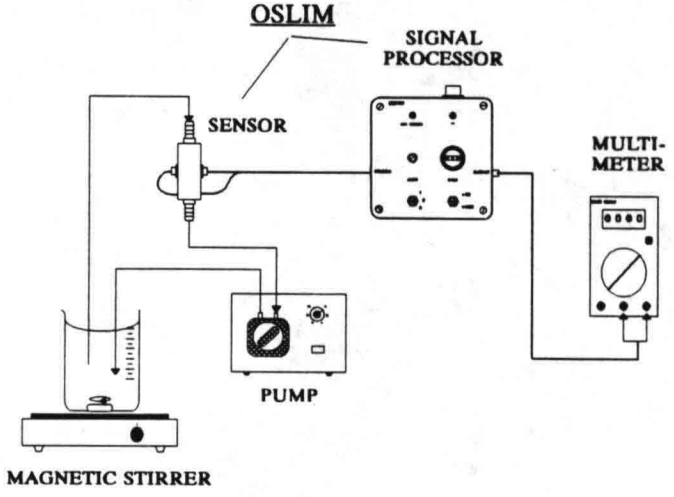

Figure 2.3.2 Outline of experimental set-up used for testing an Oslim.

2.3.1 The influence of the flow velocity on the reading of an Oslim

A suspension of China Clay, supplied by Blythe Colours B.V. Maastricht (The Netherlands) under product code Kaolin RM.225 GTY powder, and tap-water was contained in a beaker. The beaker was placed on a magnetic stirring plate (Barnstead | Thermolyne SP46920-26) and mixed continuously. The suspension was pumped out of the beaker through the 1.6 mm sensor, then through the peristaltic

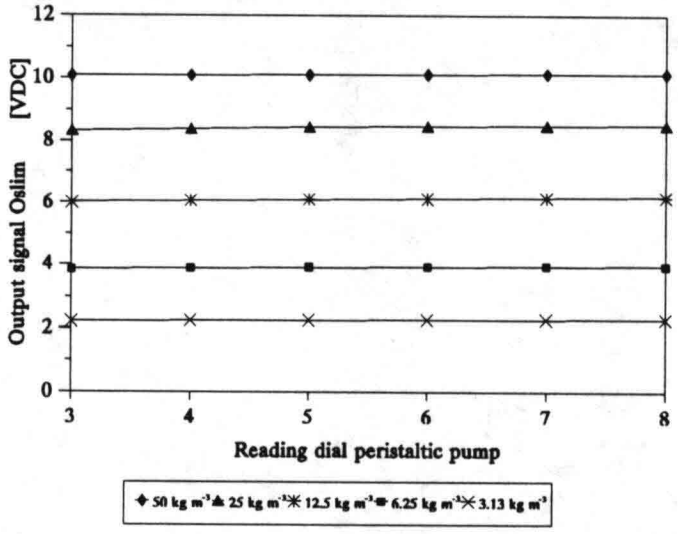

Figure 2.3.3 The influence of the flow rate on the reading of an Oslim.

pump and entered the beaker again. An outline of this set-up is given in figure 2.3.2. The influence of a varying flow velocity on the reading of the Oslim was measured. This procedure was repeated for different concentrations of the suspension. The results of these tests are presented in figure 2.3.3. A slight increase of the output signal was observed when the flow velocity was increased. However, the influence of a change in flow velocity with the pump used on the reading of an Oslim was very small. Another conclusion of this test was that reading of the Oslim was constant, although the peristaltic pump was generating a slightly unsteady flow.
There was no change in the reading of the Oslim when the direction of the flow through the sensor was reversed. This was checked using suspensions with a concentration between 2 $kg \cdot m^{-3}$ and 50 $kg \cdot m^{-3}$ and for flow rates varying between 5 and 12 $cm^3 \cdot s^{-1}$.

2.3.2 Comparison between a 1.6 and a 5.0 mm Oslim sensor

A 5 mm sensor was borrowed from Delft Hydraulics in March 1992. The accuracies of this sensor and the 1.6 mm sensor were determined in two tests using the same experimental set-up (see figure 2.3.2) and suspensions with concentrations ranging from $80 \cdot 10^{-3}$ $kg \cdot m^{-3}$ to 2 $kg \cdot m^{-3}$. As the glass tube diameter of the 5 mm sensor is rather large and the plastic tubes used are transparent, the sensor has to be shielded with aluminium foil to prevent the influence of changes in the surrounding light on the measurements. In the first test the maximum concentration of China Clay was 2 $kg \cdot m^{-3}$ and in the second test the maximum concentration was 0.2 $kg \cdot m^{-3}$. The flow rate through the 5 mm sensor was 4 $cm^3 \cdot s^{-1}$ and the flow rate through the 1.6 mm sensor was 2 $cm^3 \cdot s^{-1}$. The results of these tests are shown in figure 2.3.4. If the maximum concentration was about 2 $kg \cdot m^{-3}$ hardly any difference in the

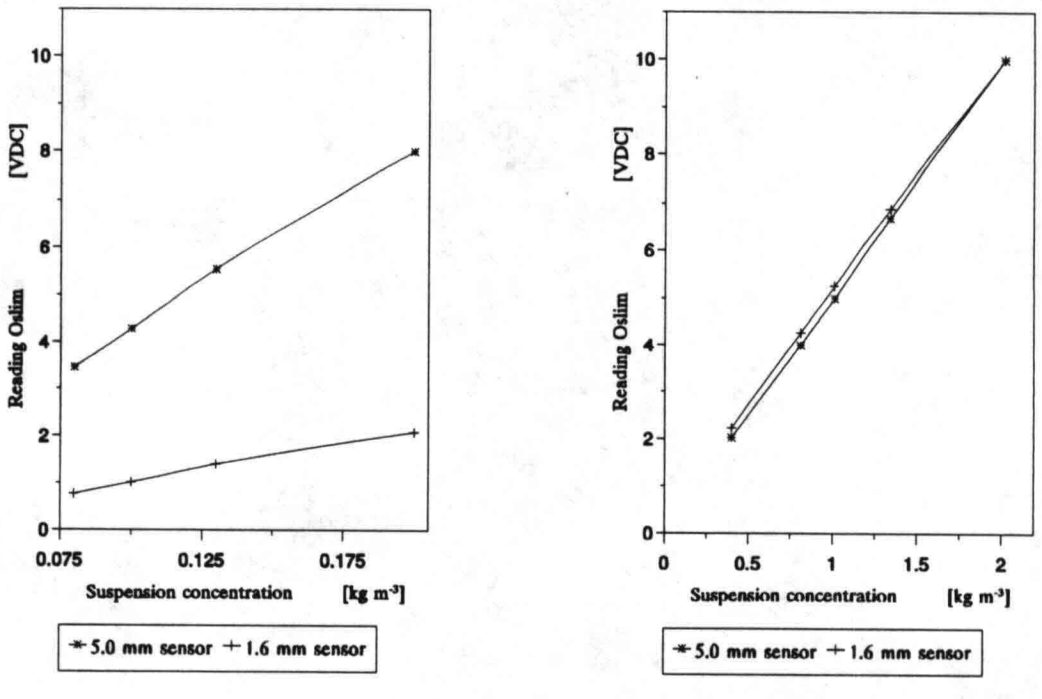

Figure 2.3.4 Performance of 1.6 mm sensor in comparison with a 5 mm Oslim sensor.

performance of the sensors was observed. However, if the maximum concentration was 0.2 $kg \cdot m^{-3}$ the 5 mm sensor gave the best results and was the most accurate. Summarizing, it is recommended to use a 5 mm sensor for measuring relatively low concentration of China Clay (< 1 $kg \cdot m^{-3}$). For higher concentrations (1-15 $kg \cdot m^{-3}$) both sensors can be used and for even higher concentrations the 1.6 mm sensor has to be preferred.
Concentrations of China Clay of up to 200 $kg \cdot m^{-3}$ were measured in the laboratory using this sensor.

3. Electromagnetic flowmeter

An experimental set-up was built in the Hydromechanics Laboratory to study the liquefaction and erosion of a cohesive sediment due to waves and current, see De Wit and Kranenburg (1992) [5]. In this set-up a magnetic flowmeter was installed in the recirculation pipe to monitor the flow rate during an experiment. Prior to installing the magnetic flowmeter it was subjected to two tests. In the first test the flowmeter was tested using an orifice plate. In the second test the influence of a non-homogeneous suspension of China Clay and tap-water on the reading of the flowmeter was examined. In the next sections a general description of the magnetic flowmeter and a description of the tests will be given.

3.1 Description

The flowmeter used is a FOXBORO 8004-WCR magnetic flowmeter with a remotely-mounted transmitter. The flow tube has a flanged body and a ceramic lining. The line size is 100 mm and the minimum and maximum flow rates to be measured are 220 and 4400 l/min. See tabel 3.1.1 and tabel 3.1.2 for more specifications of the flowtube and the transmitter, respectively.

Table 3.1.1 *Identification and specifications of the Foxboro 8004-WCR flowtube.*

Cal factor	2.9283
max pres	6.75PSI @100°F 580PSI @400°F
model	8004 WCR-C
ref no	5335394
origin	2A8818
normal temperature limits	-20 TO 55°C
approximate mass	10.0 KG

The transmitter uses a pulsed-dc technique to energize the flux-producing coils of the flow tube. The flow tube is grounded with wires to the flange of the adjoining pipes. As the process fluid passes through the magnetic field in the flow tube, low-level voltage pulses are developed across a pair of electrodes. The voltage level of these pulses is directly proportional to the cross-sectionally average velocity of the fluid. The transmitter features microprocessor-based electronics that provide automatic resetting, built-in calibration and diagnostics software for external indication of a fault and its source.

Table 3.1.2 *Identification of the Foxboro transmitter.*

model style	8000-PB10-C BD
ref no	89N10291-3A4
origin	2B8918

The 4-digit liquid crystal display (LCD) on the front of the transmitter performs several functions. During normal operation it indicates the flow rate in a choice of percentage of the upper range value or in selectable engineering units up to 999. It also indicates error codes and alarm messages. The configuration of the transmitter can be adjusted via push-buttons inside of the transmitter. Five parameters have to be entered in the transmitter. They establish the upper range value of the flow rate in the desired engineering units (parameters 1 and 2), pulse rate output (parameter 3), input signal damping (parameter 4) and display range select (parameter 5). Once adjusted, the settings will be stored in an internal memory. An extended description of the parameters is given in the instruction manuals [11,12]. The settings of the five parameters are presented in table 3.1.3. The volumetric flow unit of the readout due to these settings is $dl \cdot s^{-1}$.

Table 3.1.3 *Settings of Foxboro flowmeter (June 1992).*

Parameter no.	Setting
1	278.5
2	1
3	000.0
4	00.0
5	60.0

3.2 Tests

The performance of the flowmeter was compared to the performance of an orifice plate under the same conditions in June 1990. For this purpose a simple experimental set-up was built.

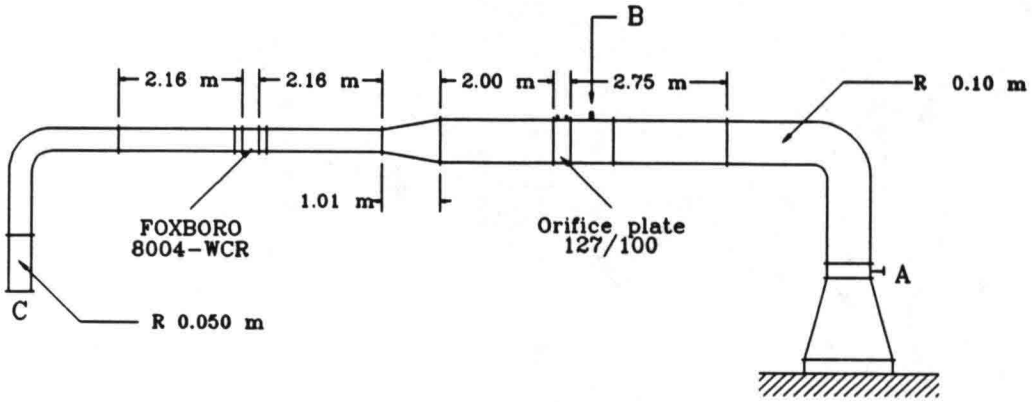

Figure 3.2.1 Experimental set-up used for testing the magnetic flowmeter.

An outline of the set-up is shown in figure 3.2.1. The orifice plate used had the following specifications: 127/100, $\beta=0.6$, colour code: yellow. During the test the flow rate was varied by adjusting valve A and the readings of flowmeters were determined. The result of this experiment, see figure 3.2.2, show that the performance of the Foxboro flowmeter meets very well the specifications given by the supplier.

After this experiment the flow rate was adjusted to 10 $l \cdot s^{-1}$. Then a suspension of China Clay and tap-

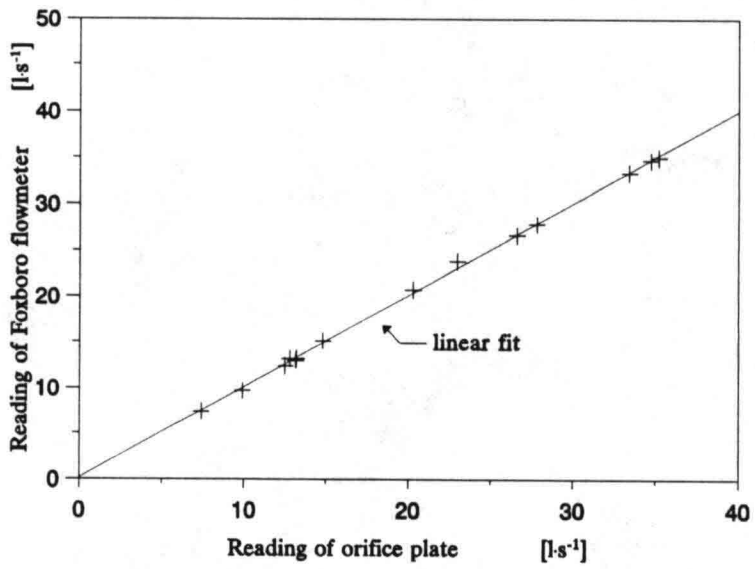

Figure 3.2.2 Comparison between the Foxboro magnetic flowmeter and an orifice plate (127/100, $\beta=0.6$, colour code: yellow).

water (concentration 400 $kg \cdot m^{-3}$) was injected at position B (see figure 3.2.1) in such a way that the total average flow rate was not changed. The reading of the flowmeter was continuously monitored during this process. Samples were taken at position C in order to determine the concentration of the China Clay. After one minute the injection of China Clay was stopped. During this test the reading of the flowmeter did not change. The concentration of China Clay at position C varied between 0 and 15 $kg \cdot m^{-3}$.
These results confirmed not only the specifications given by the supplier, but also the ability of the Foxboro flowmeter to measure the flow rate of a suspension of China Clay.

4. Thermometer

Since April 1992 a digital thermometer (Fluke model 2180A) has been available in the Hydromechanics Laboratory. It is a portable, five digit resistance temperature device (RTD) thermometer with a round-bar like sensor. The temperature is measured in the tip of the sensor. Using a 390Pt RTD type sensor, temperature measurements are possible over a range of -200°C to +204°C with a resolution of .01°C. The maximum error is about 0.04°C in this configuration. The reading can be switched from Fahrenheit to Celsius and vice versa with a front panel switch. This instrument features dual slope A/D conversion and a microcomputer control logic. There is also a banana jack connector for an analogue output (100 mV per degree). Digital output is also possible. A warm-up time of 5 minutes should be taken into account before the thermometer is used. For further information see the instruction manual of the Fluke thermometer [10].

5. Electromagnetic velocity meter

Measuring the flow velocity of a suspension of saline water and China Clay makes high demands upon the device used. Such a suspension is highly opaque which makes it almost impossible to use a laser doppler anemometer for this purpose. Furthermore, the clay particles have a very strong tendency of polluting several devices, such as hot-film or impeller-like fluid-velocity meters. Consequently it is not recommendable to use one of these devices for measuring the flow velocity of a China Clay suspension. The only device which should be suitable in such an environment is an electromagnetic fluid-velocity meter. In the laboratory a four quadrant electromagnetic fluid-velocity meter (E.M.S., E-type) has been used, which was developed and supplied by Delft Hydraulics. In the next sections a brief description of the principle of operation and the experiences gained with it will be described.

5.1 Description

The E.M.S. is in fact the inside-out version of the electromagnetic pipe flow meter employing Faraday's Induction Law for measuring the velocity of a conductive fluid moving across a magnetic field. This field is generated by a pulsed current through a small coil inside the body of the sensor. Two pairs of diametrically opposed platinum electrodes sense the voltages produced by the flow past the sensor. These voltages are proportional to the sine and cosine of velocities parallel to the plane of the electrodes. The low level output signals are converted to high level output signal by means of an amplifier. The magnitude of the velocity and its direction, with respect to a reference, can be derived by application of common geometry.
The sensor has an ellipsoidal shape (11 x 33 mm) and a small sensing area. The sensing area is a cylinder just below the ellipsoidal sensor with diameter 33 mm and height 5 mm. This makes it possible to measure velocities up to 0.5 cm from the bottom and side-walls.
The range is variable; 0 to +/- 1 $m \cdot s^{-1}$ or 0 to +/- 5 $m \cdot s^{-1}$. The maximum error is +/- 1% of the selected full scale. However, using the 0 to +/- 1 $m \cdot s^{-1}$ range and for absolute velocities lower than 20 $cm \cdot s^{-1}$ the maximum error is +/- 0.5 $cm \cdot s^{-1}$. These specified accuracies apply to reference conditions after calibration. The instruments were calibrated in a towing tank (ISO 3455) and a calibration certificate is supplied with every E.M.S. by Delft Hydraulics. The zero-flow stability is better than 1 $cm \cdot s^{-1}$ per day. The standard response is set for 5 Hz, but can be altered to 10 Hz by means of two switches in the signal processor. The noise level may increase in the 10 Hz setting. The response of the flow meters in the Hydromechanics Laboratory is set at 5 Hz.
The probe must be kept as clean as possible. Use a wetted sponge of "scotchbrite" to clean the probe, never use chemicals. Before starting a measurement it is recommended to immerse the probe for at least half an hour in the medium in which it will be used. If the probe has been dry for a long time, it is advised to place it in water for several days. Furthermore, it is recommended to avoid electrical currents close to the probe during a measurement.
If several electromagnetic flow meters are employed in an experiment, they may interfere. However, the interference is negligible when the distance between the probes is more than 15 cm.
For more detailed specifications see the technical manual [6] and the calibration certificates.

5.2 Experiences

Prior to using an E.M.S., the sensor is placed in a stagnant fluid identical to the fluid in which the measurement will be made. The X and Y output are adjusted for 0.00 Vdc by means of the potentiometers on the front panel. Experiments in stagnant tap-water with a constant temperature show that there is a shifting of the zero setting proportional to time and is on average $5 \cdot 10^{-3}$ Vdc per hour. Therefore it is recommended to measure the average output in the stagnant fluid before ánd after the actual measurement. With these zero measurements and their points of time of making, the actual measurements can be easily compensated for the shifting of the zero setting if the point of time of the measurement is known.
Using the E.M.S. in the so-called Sediment Transport Flume, it was observed that the zero setting changed when the probe was moved in a cross-section of the flume. This phenomenon made it impossible to measure a velocity profile during an experiment. By mounting ground cables from the top of the metal rod of the sensor to the rail on top of the Sediment Transport Flume this malfunction was remedied. Furthermore it is recommended to use an isolation-transformer to reduce the effects of ground loops when data from several velocity meters are logged on a personal computer. Only the power for the computer and the data-acquisition set should be supplied by the secondary coil of the transformer, whilst the primary coil is connected directly to mains. The electromagnetic velocity meters and all other instruments should be connected directly to mains. In this configuration the output signals of the instruments used are measured relative to the voltage of the data acquisition set and a generation of an capacitive potential is not possible.
Some tests were carried out in the Sediment Transport Flume to check the feasibility of an E.M.S. for measuring velocities in saline water (salinity 5‰) and in suspensions of saline water and China Clay with a concentration of up to about 500 $kg \cdot m^{-3}$. A description of these tests will be given next.

The flume was filled with clear saline water (salinity 5‰, water depth 25 cm) and an approximately 5 cm thick consolidated layer of China Clay with a concentration of about 500 kg m^{-3}. The flume is provided with a remote-controlled measuring carriage and its velocity and direction of motion are adjustable. E.M.S. sensor E015 attached to a gauging-rod was installed on the carriage in such a way that the X-direction of the sensor corresponded with the longitudinal axis of the flume. The ellipsoid of the sensor was set at 12 cm from the water-clay interface. The X-output of signal-processor was logged on a personal computer, while the sensor was towed several times through the fluid with a constant velocity. The velocity of the carriage was varied and it was determined by measuring the time needed for the carriage to cover a certain distance.
Subsequently the sensor was lowered until one half of the ellipsoid had disappeared into the clay and in this setting several tests were carried out too. Finally the sensor was set at 2 cm from the flume bottom and again several tests were carried out.
The data logged on the personal computer were corrected for the zero-offset potential and converted to velocities by using the calibration certificate supplied by Delft Hydraulics. The results of these tests are listed in table 5.2.1.
The results of these experiments show that an E.M.S. is probably suitable for measuring velocities in suspensions of China Clay and saline water and it seems to be possible to measure velocities in a moving fluid-mud layer.

Table 5.2.1 *Comparison of velocity measurements.*

Position of sensor	Average velocity (distance/time) [cm·s^{-1}] stad.dev. = 0.08	Average velocity (logged data) [cm·s^{-1}] stad.dev. = 0.4
12 cm above water-clay interface	-3.39	-3.2
	3.34	3.2
	-3.34	-3.4
	3.35	3.3
2 cm above the flume bottom	-3.36	-3.5
	3.35	3.1
	-7.87	-7.3
	7.73	7.0
at water-clay interface	-7.74	-7.8
	7.73	7.6

6. Wave height meter

In the experiments of De Wit [5] wave height meters were used in suspensions of saline water and China Clay. Prior to these experiments these instruments were tested in order to check their operation in suspensions of China Clay and saline water, for they are not designed for such media. In the next sections the instrument and its principle will be described as well as the tests which were carried out.

6.1 Description

The wave height meter was supplied by Delft Hydraulics and is composed of two parts; a gauge with an integral pre-amplifier and a separate main-amplifier.
The gauge consists of two parallel stainless steel rods, mounted underneath a small box, containing the pre-amplifier. The rods act as electrodes of an electric resistance meter. The electric resistance measured between the electrodes is inverse proportional to the instantaneous depth of immersion and the specific conductivity of the water. To avoid the effect of conductivity fluctuations, a platinum reference-electrode is mounted between the rods at the lower end of the gauge.
The main-amplifier contains a power-supply, a variable gain amplifier, a zero shift and a panel meter, indicating the instantaneous fluid level. Several ranges can be selected at the main amplifier, namely ranges of 5, 10, 20 and 50 cm. The linearity of the range selected is better than +\- 0.5%. The frequency characteristics of the system permit measurements from 0 up to 10 Hz and there is an analogue output available. For more information the reader is referred to the technical manual [7].

6.2 Instructions for use

When the gauge has been kept dry for a long period, it should be cleaned and the electrodes should be placed under water for a few hours before starting the actual measurement. At the beginning of each experiment it is recommended to clean the rods and the reference-electrode of the gauge with a piece of cloth soaked in a three percent solution of nitric acid (HNO_3) or "degreaser", the latter is generally used in the Hydromechanics Laboratory.
Furthermore it is recommended to allow the instrument a warm-up period of at least half an hour.
After the electronics have warmed up the instrument must be calibrated. For that purpose the probe is attached to a point-gauge, for instance. The depth of the probe is chosen in such a way, that during the calibration and the actual measurement the top of the reference electrode is immersed for at least 4 cm. A recommended immersion-depth is half the value of the selected range plus 4 cm, measured from the top of the reference electrode in the stagnant fluid. Then the pointer of the indicating meter on the front panel of the main amplifier and also the output voltage must be adjusted to its centre-scale position which corresponds with 0.0 Vdc output. After these preparations the calibration of the instrument can be carried out, i.e. changing the immersion-depth of the probe by means of the point-gauge and measuring the change in the output voltage. It is recommended to determine at least five calibration points and calculate the best straight line through these points with a least squares approximation.
When several wave height meters are used simultaneously and close to each other, they might influence each other. However, for distances larger than 20 cm, this influence is negligible.

6.3 The influence of clay and salt on the linearity

The described wave height meters are not designed for employment in saline water. As a result of that some doubts arose about the linearity of the device in saline water and a suspension of China Clay. Therefore some experiments were carried out to measure the linearity under these conditions. In these experiments only the devices built between 1974 and 1978 were tested. A description of these tests and the results will be given next.

A large tank was filled with a fluid. A probe attached to a point-gauge is immersed in the fluid. The output voltage (V) is measured with a voltmeter. The change in water depth in the tank due to a change of the immersed depth (H) of the probe is negligible. In this configuration five-point calibrations were carried out for three ranges, namely 5, 10 and 20 cm and several fluids, including tap-water, saline tap-water and saline tap-water with China Clay.

The best straight line ($V = aH + b$) was calculated using a least squares approximation [2]. The slope (a) and its standard deviation (σ_a) are shown in table 6.3.1. The regression coefficient r [2] is also printed in table 6.3.1. If r is unity, the data points fit exactly the calculated straight line.

Table 6.3.1 *Influence of salt and China Clay on the linearity of a wave height meter.*

Range	5 cm			10 cm			20 cm		
	a	σ_a	r	a	σ_a	r	a	σ_a	r
0‰ NaCl 0 kg·m^{-3}	4.11	0.17	0.99999	2.07	0.094	0.99999	1.06	0.027	0.9983
5‰ NaCl 0 kg·m^{-3}	4.11	0.007	0.99999	2.02	0.006	0.99996	1.02	0.002	0.99998
10‰ NaCl 0 kg·m^{-3}	4.09	0.011	0.99997	1.98	0.010	0.99992	1.01	0.003	0.99996
5‰ NaCl 0.14 kg·m^{-3}	4.08	0.025	0.99990	1.99	0.013	0.9998	1.01	0.005	0.99990
5‰ NaCl 0.41 kg·m^{-3}	4.08	0.017	0.99994	1.999	0.007	0.99996	1.01	0.004	0.99994

The results show that the wave height meters are applicable in water which contains low concentrations of salt and mud.

7. Pore-pressure meter

A very important parameter in the liquefaction process of mud is the pore-pressure. Water waves progressing over a muddy bed are sometimes capable of generating a change in pore-pressure in the bed resulting in a liquified layer of mud. As a consequence, measuring this parameter in experiments to come is one of the most important objectives. However, initially hardly any know-how was present about measuring pore-pressures in a muddy bed. Therefore inquiries were made and we ended up at Delft Geotechnics. On the advice of prof.dr.ir. F.B.J. Barends and J. van der Vegt of that laboratory Druck PDCR 81 transducers were purchased. A description of this device and the adjustments made for a proper operation in the Hydromechanics Laboratory will be given in the next section.

7.1 Description

The Druck PDCR 81 is a miniature high-performance pressure transducer. An outline of this transducer is given in figure 7.1.1. The transducer is available in several operating ranges, from 75 mbar up to 35 bar and is supplied with a ceramic filter. The pore-size of the ceramic filter is about 3 μm. Only the pore fluid can pass the filter and in this way only the pore-pressure is measured. The

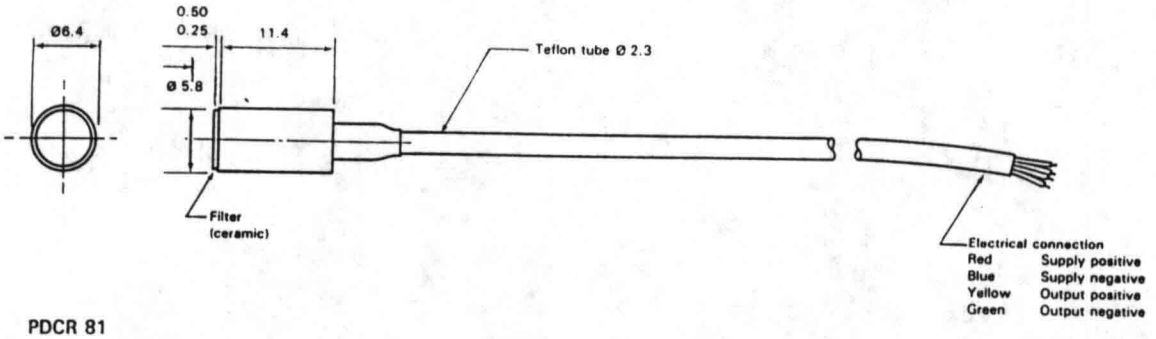

Figure 7.1.1 Outline of Druck PDCR 81 pressure transducer.

pore-pressure is measured with respect to a reference pressure. Normally this will be the atmospheric pressure, to which the transducer is connected via a vented Teflon cable. For this reason special attention should be paid to avoid squeezing of the cable, and of course to measure the changes in the atmospheric pressure if the measurements take more than one day.
The pressure transducer is connected with a Druck DPI 260 digital pressure indicator. This device measures and indicates the pressure in any specified scale units and provides accuracies of +/- 0.1% of the full scale (F.S.). Both digital and analogue outputs are available via a BCD plug. If the analogue output option is chosen, 10 Vdc corresponds to the maximum range of the transducer.
Further specifications of the pressure transducer are printed in table 7.1.1.

Table 7.1.1 *Specifications of PDCR 81 with a range of 75 mbar.*

effective diameter of membrane	2.54 mm
displacement of membrane at 75 mbar	0.84 μm
internal volume change from 0 to 75 mbar	0.0022 mm^3
Combined non-linearity & hysteresis	± 0.2% B.S.L.*)
Thermal zero shift	± 0.05% F.S./°C
Thermal sensitivity shift	± 0.2% of reading/°C
Operating temperature range	-20° to 120°C

*) B.S.L. : Best Straight Line

Assuming the specifications presented in table 7.1.1 and figure 7.1.1 it can be calculated that the fluid in the filter is displaced over $1.11 \cdot 10^{-6}$ mm as the pore-pressure changes 1 mbar. As a consequence of the very small displacement of the fluid the filter will not be clogged by mud particles.

In the Hydromechanics Laboratory four of these pore-pressure meters are present; three with a range of 75 mbar and one with a range of 350 mbar. Every meter has its own calibration certificate supplied by the manufacturer. The measured accuracy of the 75 mbar pore-pressure meters is ± 0.073% of range, which corresponds with ± 5 Pa. For further information refer to the technical manual and the calibration certificates [9].

7.2 Instructions for use

Prior to using the transducers in an experiment, the pores in the filter have to be filled completely with water. This is done by submersing the transducer in a beaker containing distilled water and placing them both under vacuum. It is recommended to hold the transducer under vacuum for at least one day, then the air in the pores of the filter should be replaced completely by water. If there should be any air left in the filter, the pore-pressure meter will not reproduce an instantaneous change of the immersed-depth of the transducer. An exponential path will be observed instead.
At Delft Geotechnics it was found that such a ceramic filter could be de-aerated only once if the transducer had been employed in a clay-like soil. This problem was remedied by installing a custom built sintered steel filter (SICA R5) with a pore-size of 5 μm. These filters were ordered from Delft Geothechnics in June 1990. Our contact at Deft Geotechnics for this order was ing. P.F. Stojansek. At the moment of writing, August 1992, all transducers in the Hydromechanics Laboratory are provided with these filters.
As the pressure transducer is sensible to temperature changes, the temperature of the surrounding fluid should be monitored during a measurement.
In order to get familiar with this measuring device, some tests were carried out. An example of such a test will be described in the next section.

7.3 Response of pore-pressure meter to regular waves

In the Sediment Transport Flume two different pore-pressure transducers were mounted vertically in a cross-section at different elevations from the bottom. The flume was filled with clear tap-water and the water depth was 50.9 cm. The filters of the transducers were not removed and they pointed in upward direction. The positions of the filter top, the serial numbers and the ranges of the transducers are listed in table 7.3.1.

Table 7.3.1 *Specification of test experiment for pore-pressure meters.*

Transducer no.	1	2
elevation [cm]	20.7	17.6
serial number	5443/90-2	7466/91/2
range [mbar]	0 - 350	0 - 75

In the same cross-section a wave gauge was installed. The data of the different devices were recorded on a personal computer by means of a data-acquisition set. The flume is provided with a mechanical wave maker, which is only capable of generating regular waves. The wave period was set at 1.5 s. After calibrating the wave gauge, waves with a fixed wave height were generated. After the switching-in effects had damped, the actual measurement was started and lasted for about one minute. Then the wave height was increased and another measurement was made.
After converting the data, the one-minute averaged wave - and pressure amplitudes were determined. The results are printed in table 7.3.2. In this table also the results are listed of a calculation of the expected values according to linear short-wave theory [1]. According to that theory the amplitude of the pressure fluctuations $\hat{p}$ generated by progressive waves at a distance z below the average water level is:

$$\hat{p} = \rho g a_w \frac{\cosh k(h+z)}{\cosh kh} \tag{7.3.1}$$

where
- a_w : wave amplitude,
- k : wave number,
- ρ : density of the fluid and
- g : gravitational acceleration.

The wavelength L of a progressive wave with period T follows from:

$$L = L_0 \tanh \frac{2\pi h}{L} \tag{7.3.2}$$

where $L_0 = \frac{gT^2}{2\pi}$.

Table 7.3.2 *Comparison between measured and calculated pressure fluctuations.*

range of pore-pressure transducer [mbar]	z [m]	measured average wave height [cm]	measured average pressure amplitude [Pa]	calculated pressure amplitude [Pa]
75	0.302	19.4 ± 0.5	122 ± 5	122 ± 6
350	0.333	19.4 ± 0.5	118 ± 3	118 ± 6
75	0.302	31.2 ± 0.5	203 ± 5	196 ± 9
350	0.333	31.2 ± 0.5	197 ± 5	191 ± 9

Using the experimental data the wave number $k=2\pi L^{-1}$ can be estimated and the pressure amplitude $\hat{p}$ can then be calculated.
From the results presented in table 7.3.2 the conclusion can be drawn that the experimental results correspond very well with what may be expected according to linear short-wave theory and consequently that the Druck PDCR-81 pressure transducers perform very well.

8. Conductivity probe

8.1 Description

The electrical conductivity is the reciprocal of resistivity. According to Weast [4] this quantity is defined by:

$$R = r\frac{l}{A} \tag{8.1.1}$$

where R is the resistance of a uniform conductor, l is its length in the direction of the current, A is its cross sectional area and r is its resistivity. The resistivity is usually expressed in Ohm-centimetres [Ω·cm]. Consequently the conductivity is expressed in $\Omega^{-1}\cdot cm^{-1}$, which corresponds with Siemens per cm [$S\cdot cm^{-1}$].
The conductivity of clear water is primarily determined by the presence of ions, the conductivity of distilled water, for instance, is very low because of the absence of ions. An other important parameter is the temperature. When the temperature changes the mobility of ions will change resulting in a change in conductivity.
The conductivity of water with a constant composition of ions decreases if a certain amount of sediment is added. The principle of a conductivity concentration meter is based on this phenomenon. At Delft Hydraulics such a concentration meter was developed and it consists of a probe and a signal processor. The probe is composed of four separate electrodes and is supplied with an alternating current in order to eliminate polarisation effects. It is shaped in a wedge form with a measuring volume of about 3 mm^3. The operation range of sediment concentrations within which this device can operate accurately is from about 250 to 1300 $kg\cdot m^{-3}$. Its accuracy is estimated at about 10% of the local concentration [3].

8.2 Instructions for use

The conductivity meter supplied by Delft Hydraulics is designed to measure concentrations of sediment in fresh water. However, in the experiments of De Wit [5] salt water was used with a salinity of 5‰. As a consequence, the conductivity meter present in the Hydromechanics Laboratory was adjusted to operate properly in this environment.
The conductivity concentration meter has to be calibrated before or after every measurement, for the conductivity change of the pore water caused by a concentration change depends on the type of

sediment and the temperature. Therefore the instrument should be calibrated with exactly the same pore water and sediment. In order to perform a proper calibration the following instructions should be carried out carefully.
First of all the probe should be cleaned with a brush in tap-water. Then the probe should be placed in pore water in which no sediment is present and record the reading (U_{clean}) of the conductivity concentration meter. Next the probe has to be placed in a suspension with the maximum concentration of sediment (C_{max}), that will be expected in the actual measurement and the reading (U_{max}) should be recorded. The volumetric fraction of the maximum sediment concentration should be less than 50 %. The device is now ready for use and the concentration C_t of an unknown suspension is determined by substituting the reading of the concentration meter U_t in the following equation:

$$C_t = C_{max} \frac{U_{max}}{U_{max} - U_{clear}} \frac{U_t - U_{clear}}{U_t} . \qquad (8.2.1)$$

Following the instructions previously described, the measurements are compensated for the conductivity of the clear pore water.

9. Balances

In the physico-chemical laboratory two devices are available for the determination of weight; The Sartorius Research R 200 D and a Sartorius Industry IB 31000 P. Outlines of these balances are shown in figure 10.1.

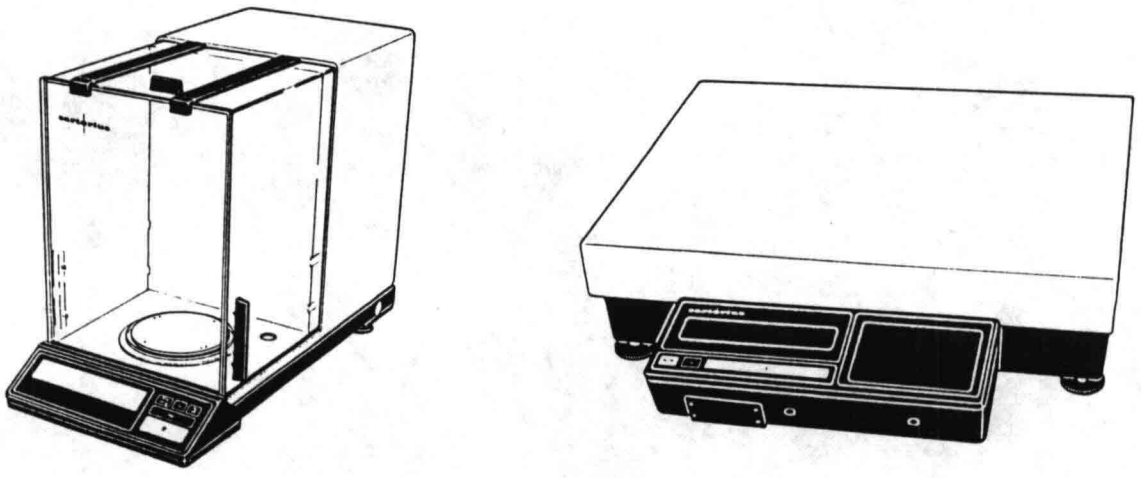

Figure 10.1 Balances available in the physico-chemical laboratory.

The balances should be placed at a place where they are not exposed to heat radiation, drafts and

vibrations. To determine the weight of a sample as accurate as possible the balances should be calibrated. If the balance is unloaded, it will carry out an internal calibration when the Cal key is pressed. Some specifications of the devices are presented in table 10.1. See for more information the installation and operating instructions of the two devices [17,18].

Table 10.1 *Specifications of weighing devices.*

Model	Sartorius Research R 200 D	Sartorius Industry IB 31000 P
Weighing capacity	42 / 205 g	31 kg
Readability	0.01 / 0.1 mg	1 g
Standard deviation	≤ ±0.02 / 0.1 mg	≤ ± 0.5 g
Max. linearity	≤ ±0.03 / 0.2 mg	≤ ± 1 g
Stabilization time (typical)	7 / 4 s	2 s
Ambient temperature range	+10 - +40°C	0 - +40°C
Sensitivity drift within +10°C - +30°C	≤ ± $2 \cdot 10^{-6}$ /°C	≤ ± $4 \cdot 10^{-6}$ /°C

10. Filtration

The most commonly used method for measuring the suspended sediment concentration is by means of filtration and gravimetry. In the next sections the procedure used at the Hydromechanics Laboratory will be described for determining the concentration. Furthermore specifications will be given of the filters and apparatus used.

10.1 Filtration procedure

The procedure to be described yields the suspended sediment concentration as accurate as possible. This procedure is very labour-intensive and therefore it is advised to consider previously how accurate the determination has to be. If one is content with a rough determination, several actions in the procedure may be omitted thus making the determination less labour-intensive.
The following actions should be made to determine the suspended sediment concentration as accurate as possible.

I. Place the filter on the support plate of the filter funnel and rinse it with distilled water in order to remove all loose or soluble material.
II. Place the filter with a smooth-tip forceps in a clean Petri dish and dry the filter in an oven

for half an hour at 100°C. From now on the filter should only be touched carefully by a smooth-tip forceps.

III. Remove filter from oven and place it in a desiccator for two hours in order to cool down and to prevent the adsorption of water. Make sure that the silica gel in the desiccator is not fully saturated with water. If the colour of the gel is pink, the gel is fully saturated and it should be dehydrated first. The gel is blue in a dehydrated state.

IV. Take filter out of the Petri dish and weigh the filter as accurate as possible and record its weight W_{fil}.

V. Place filter on the support plate of the filter funnel and replace the upper chamber. Clamp the filter funnel together. Apply the vacuum very slowly to avoid tearing the filter. Pour the well-mixed sample with volume V_s into the upper chamber. Rinse several times with distilled water to ensure that all the sediment is at the filter and no salt has remained in the filter.

VI. Remove very carefully the filter from the support plate and put it in a Petri dish. Place the Petri dish with filter in a oven for half an hour at 100°C.

VII. Remove filter from oven and place it in the desiccator for two hours.

VIII. Weigh filter very carefully and record its weight W_{tot}.

IX. Calculate the concentration C:

$$C = \frac{W_{tot} - W_{fil}}{V_s}. \qquad (10.1.1)$$

The precision of this determination was determined with a suspension of China Clay. The dry China Clay was suspended in distilled water, the concentration was 1 $kg \cdot m^{-3}$. The volumes of the samples were approximately 100 ml. The standard deviation found was 0.011 $kg \cdot m^{-3}$. Defining the accuracy as three times the standard deviation, the precision was about 0.03 $kg \cdot m^{-3}$.

10.2 Specifications of filters and apparatus used

The filters used are membrane filters manufactured by Schleicher & Schuell (ME23), the pore size is 0.15 μm. The filter consists of a mixture of esters, nitrocellulose and cellulose acetate. This composition gives the filter a great tensile strength. Furthermore it allows a relatively large flow rate and the material will not stick to a Petri dish, for instance, after it has dried in an oven. For more information about the filters the reader is referred to [19,20].

The filter funnel (Nalgene, Cat.No.315-0047) is designed for filtration of liquids under full vacuum using 47 or 50 mm membrane filters. An outline of the funnel is shown in figure 10.2.1. The major components are made of a special clear polysulfone, which has a chemical resistance to bases and acids. For additional chemical resistance data see the instruction manual [14]. In the physico-chemical laboratory three filter funnels are present and they are mounted on a Nalgene vacuum manifold [16].

The desiccator is constructed of transparent acrylic to permit an undisturbed view of the contents. The desiccator is manufactured by Nalgene and its dimensions (H x W x D) are approximately 46 x 31 x 31 cm^3 [15].

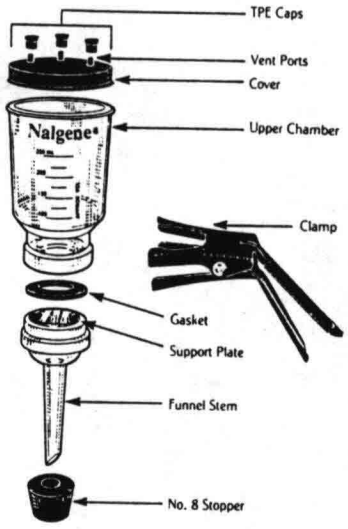

Figure 10.2.1 Outline of the Nalgene filter funnel.

11. pH measurements

The pH of a solution is measured in the physico-chemical laboratory by means of a Jenway PCP505 glass combination probe in combination with a Jenway 3040 Ion Analyser. The pH is measured with an accuracy of ±0.005 in a range of -2 to 16. The maximum solution temperature in which the probe may be used in is 100°C. The Ion Analyser is also provided with a PCT121 temperature probe, which can operate in a range of -30 to +150°C with an accuracy of ± 0.5°C.
The instrument has to be calibrated before every measurement. For the calibration two of three standard solutions are used. The pH values of these standard solution are about 4, 7 or 9, but depend slightly on the temperature, for the pH is a function of the temperature. The Jenway Ion Analyser stores the calibration data and generates a linear calibration curve, which is also stored in its memory. After calibration the pH-meter can be used. Make sure that the temperature of the solutions is constant. Place the pH- and temperature probe in the solution to be measured. The Ion Analyser will determine the pH of the solution, thereby taking possible temperature effects into account. For further information about pH measurements see [13].

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